- Further investigation is needed to determine sources of noise observed in diagrams in Figs. B11 to B14 and to try to reduce them.

2.0 NOISE SOURCE ANALYSIS

By noise Mtel implies any undesirable variation of the signal magnitude, including various interferences. Mtel has identified the following noise sources.

Variation of the Carrier Frequencies and the FFT Window Interval. Ideally each tone should have integral number of periods fitting into the FFT window. Any discrepancy would give rise to the so called "picket fence effect" which would reduce the tone magnitude and spill energy indications into the adjacent bins.

Tone Amplitude Variations. Differences in the amplitude of the transmitted carriers will be reflected as variations in their received levels and make using a single threshold for the ON/OFF decision less effective.[11] The first step in reducing effects in the tone amplitude variations is to tune the amplitudes of all tones to the same level. For example, tone levels were coarsely tuned in Figs. B13 and B14, while the fine tuning was done before taking plots in Figs. B11 and B12.

Intermodulation Products. Effects of intermodulation products are best observed on the skirts of the tones in the full scale spectrum plots (bottom traces). Further research is needed to determine contributions of nonlinearities in transmitter and receiver separately. In this experimental setup the intermodulation products are not the limiting source of noise.

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[11] Studies of the feasibility of using a single threshold are still underway. Alternatives include deriving per-tone thresholds or the use of Permutation Modulation, which has the advantage of not requiring a threshold, since the only decision that need be made is which 4 of the tones are the strongest.

Laboratory Radio Interference. Mtel was able to significantly reduce the noise by simply moving the receiver away from the transmitters within the lab, and adding some metal screens. Figures B13 and B14 were taken without this precaution, while Figures B11 and B12 show results with these measures introduced.

Round-Off and Clipping Error in A/D Conversion and FFT Calculation. The LeCroy 9400A digital oscilloscope performs A/D conversion with 8 bit precision. This is sufficient precision only for a properly loaded quantizer. The effect of the round-off can be observed on Fig. B3 as noise on all horizontal lines. For a low amplitude signal, the round-off error also creates noise in the FFT result. In addition, if the signal has too high an amplitude (*i.e.*, beyond the quantizer range), it is simply clipped to the highest allowed level. This is equivalent to nonlinear distortion, which gives intermodulation products and noise in the final results. Trade off studies of Automatic Gain Control (AGC) reduction of the dynamic range versus use of readily available 12 or 13 bit A/D converters will be undertaken.

Receiver Generated Noise. There are a large number of possible noise sources in the receive waveform, such as random Gaussian noise, the interference due to the imperfect demodulation process, etc. For example, the ripple in the middle trace in Fig. B7 comes from imperfect filtering of the upper side band in the demodulation process. More research is needed to quantify the effect of different noise sources in the receiver.

3.0 CONCLUSION

The laboratory experiments with a receiver based with FFT analysis has proved the technical feasibility of this approach. Further improvement in receiver performance is expected by reducing round-off errors and by controlling different sources of interference and noise in the system.

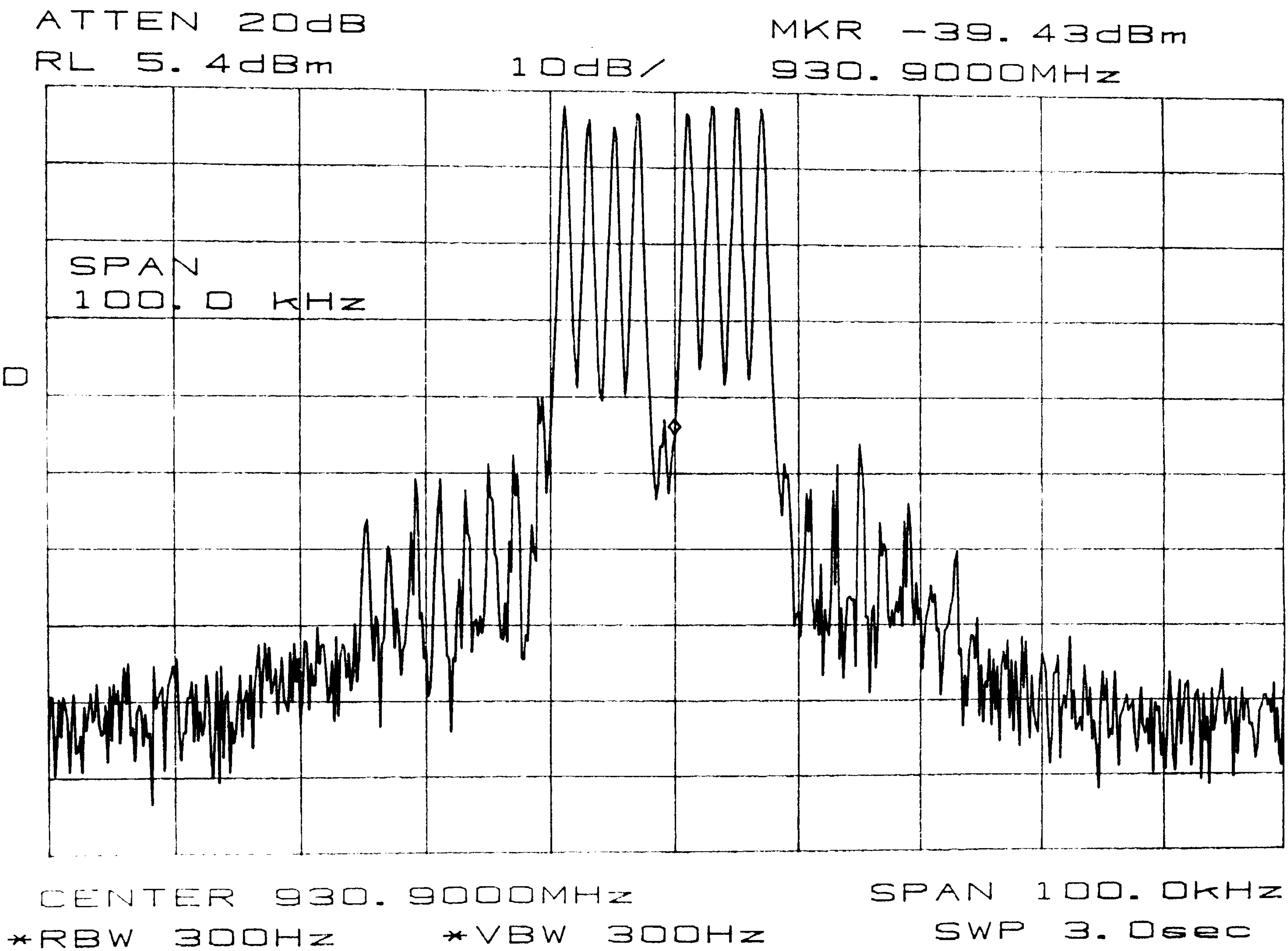

ATTEN 20dB
RL 5.4dBm
10dB/
MKR -39.43dBm
930.9000MHz
SPAN
100.0 kHz
D
CENTER 930.9000MHz
SPAN 100.0kHz
*RBW 300Hz
*VBW 300Hz
SWP 3.0sec

Figure B2

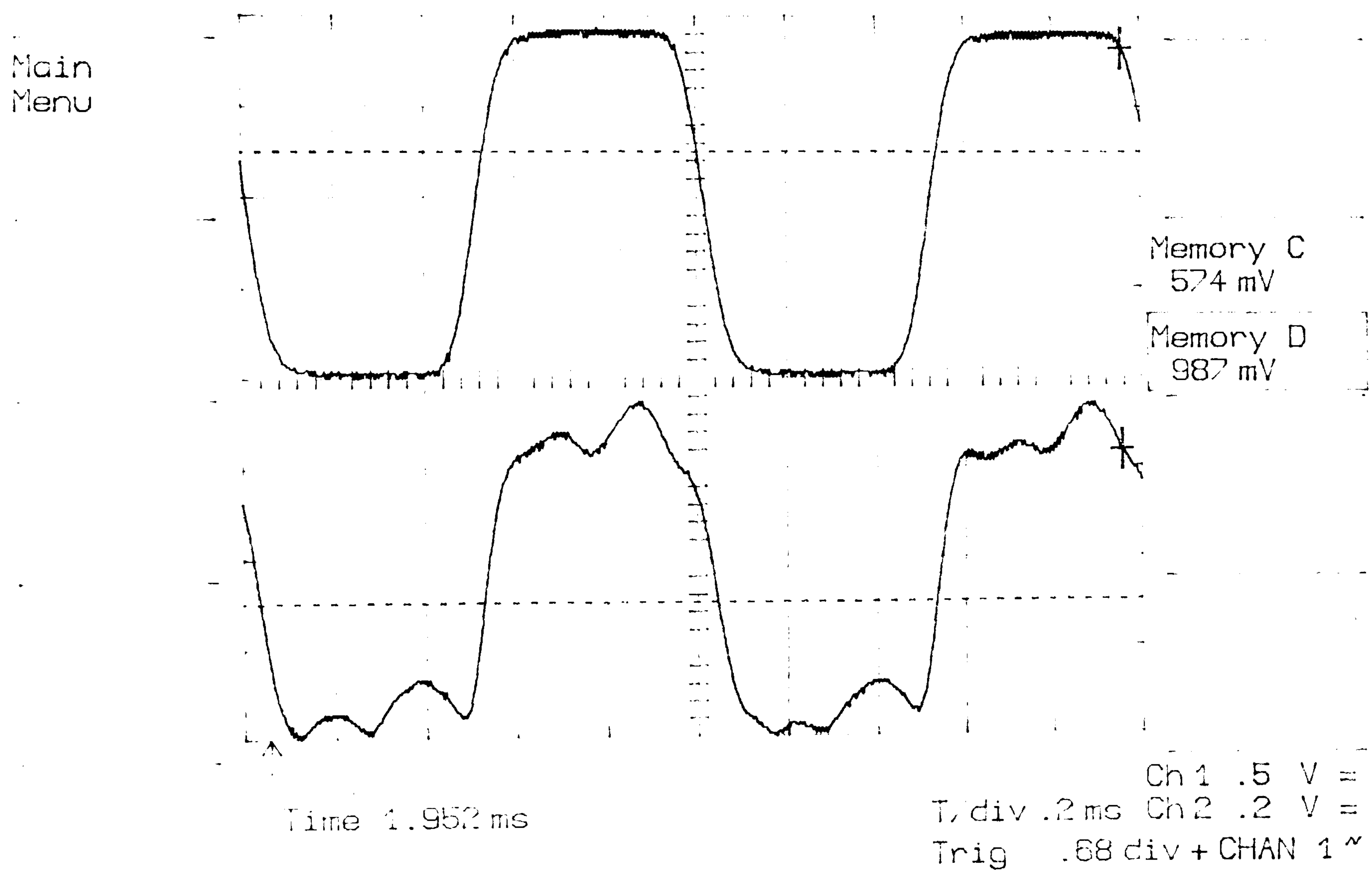

Main
Menu
Memory C
574 mV
Memory D
987 mV
Time 1.952 ms
T/div .2 ms
Ch 1 .5 V =
Ch 2 .2 V =
Trig .68 div + CHAN 1 ~

Figure B3

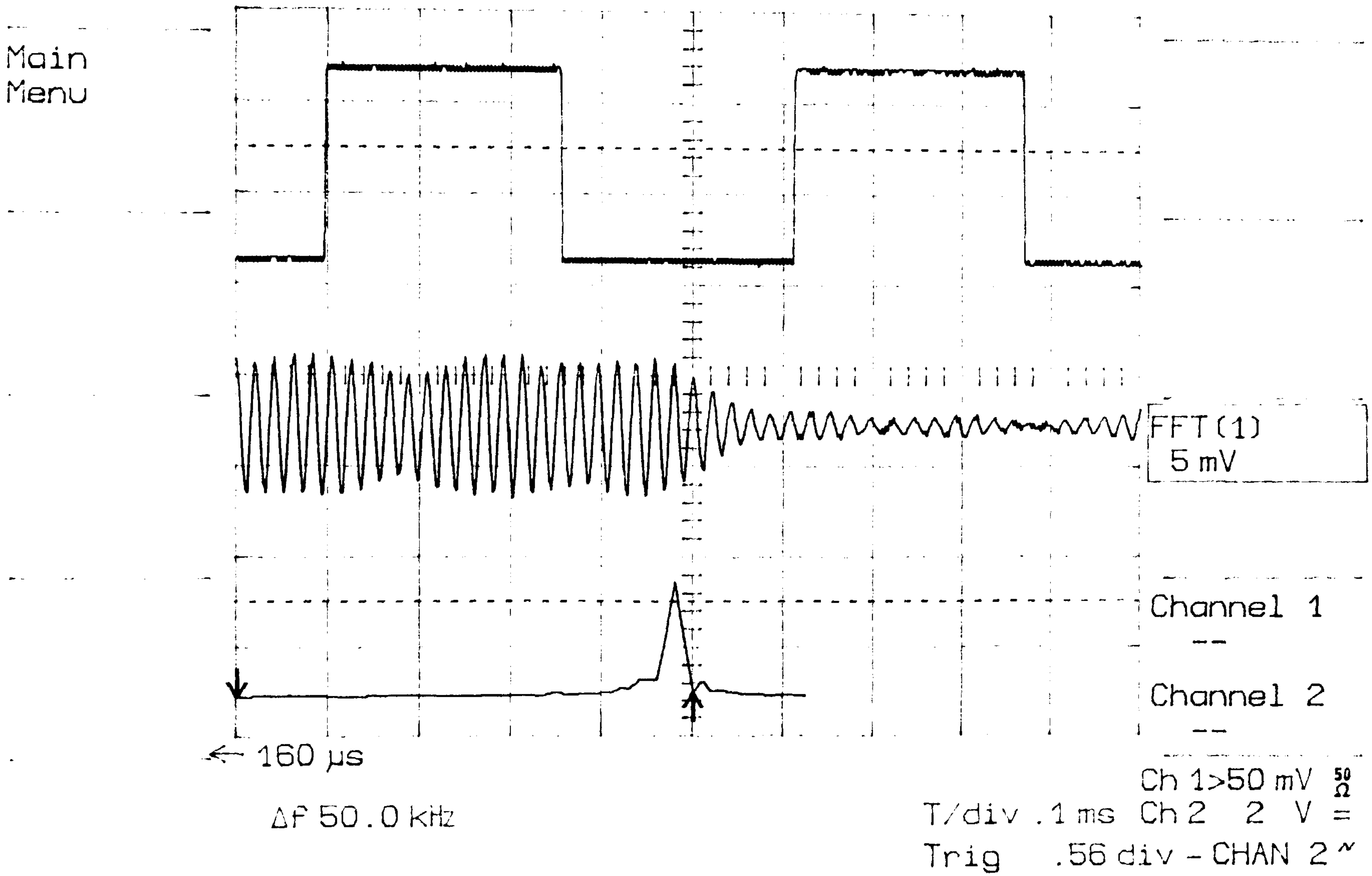

Main
Menu
FFT(1)
5 mV
Channel 1
--
Channel 2
--
← 160 µs
Δf 50.0 kHz
Ch 1>50 mV 50 Ω
T/div .1 ms Ch 2 2 V =
Trig .56 div - CHAN 2

Figure B4

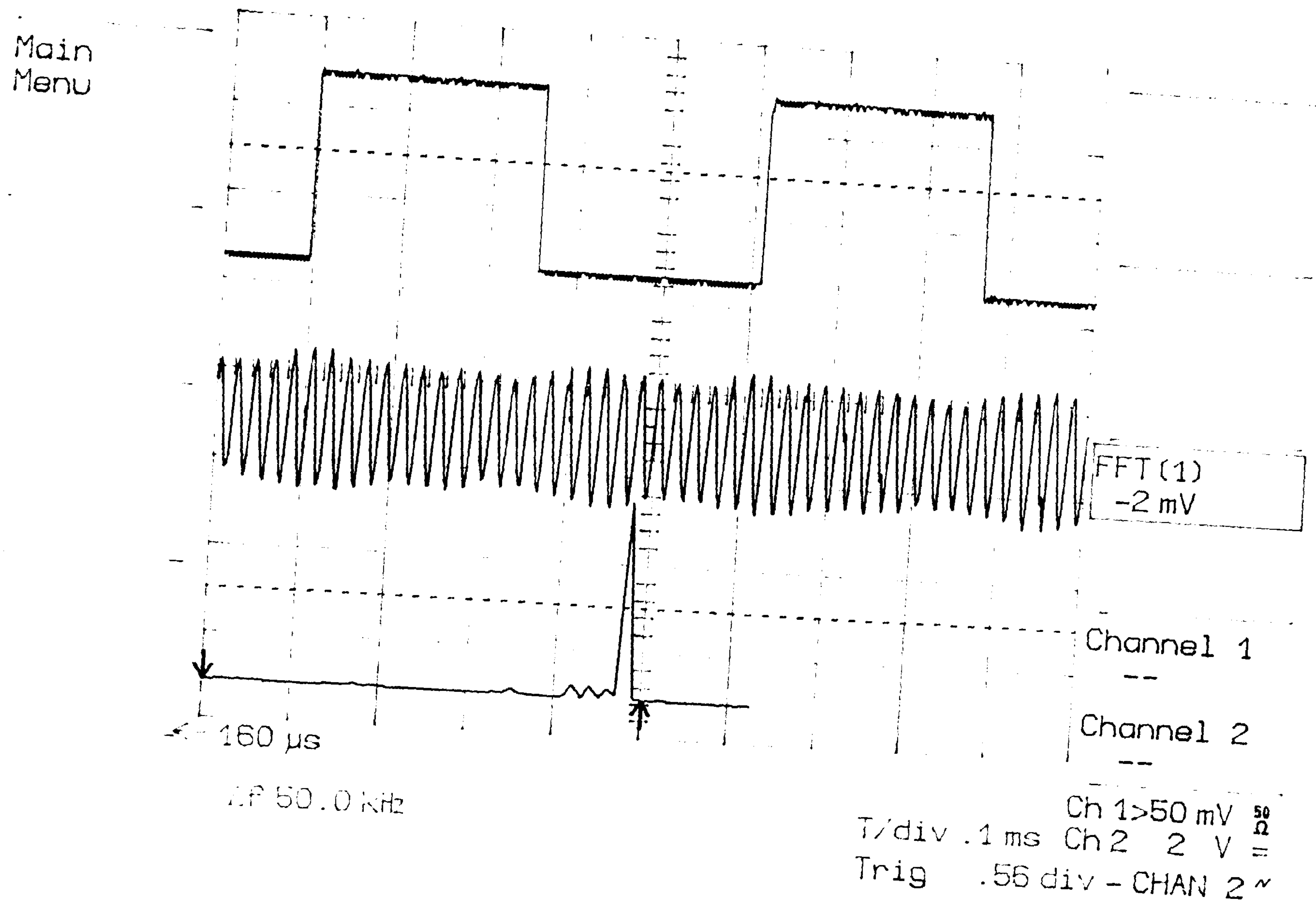

Main
Menu
FFT(1)
-2 mV
Channel 1
--
Channel 2
--
160 µs
50.0 kHz
Ch 1>50 mV 50 Ω
T/div .1 ms Ch 2 2 V =
Trig .56 div - CHAN 2 ~

Figure B5

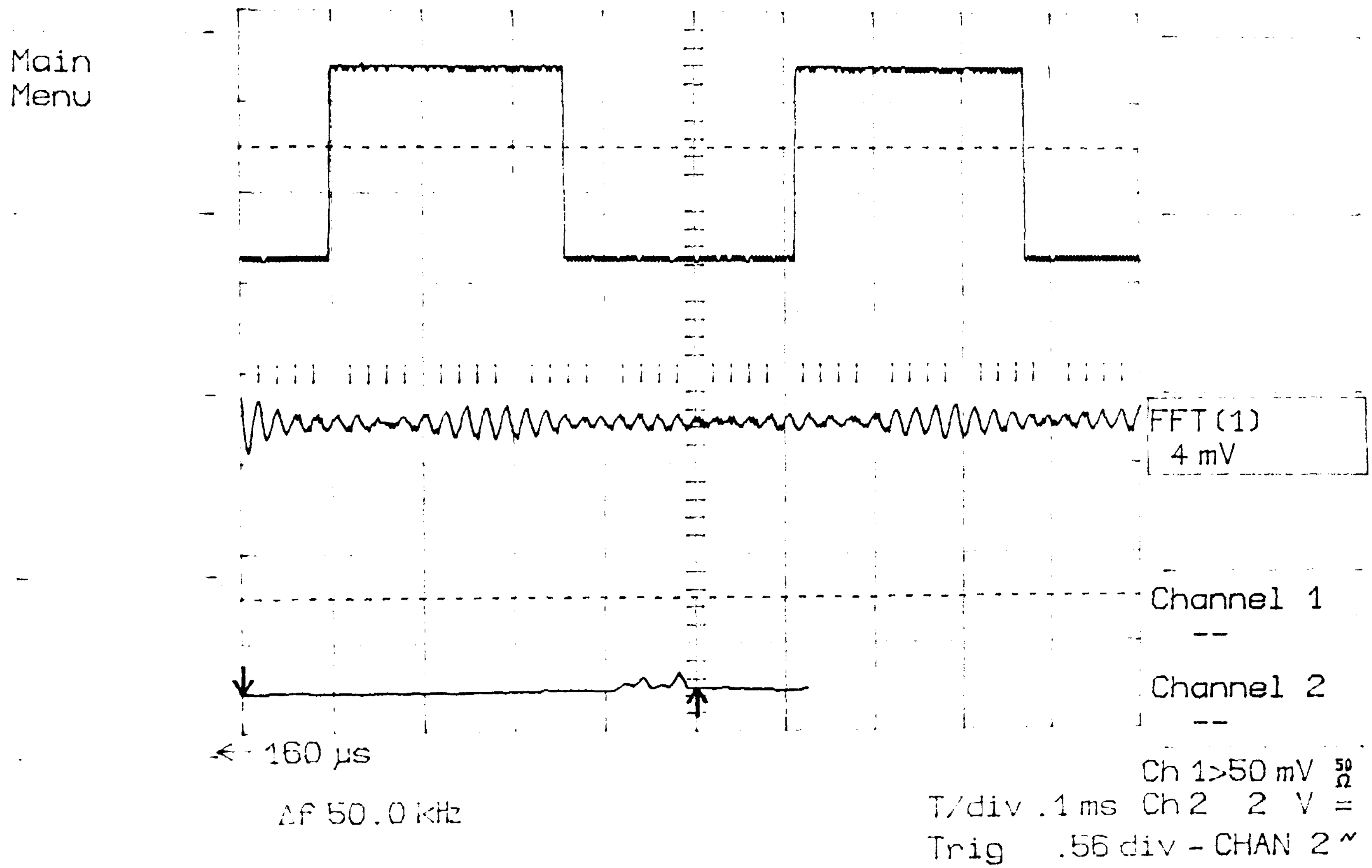
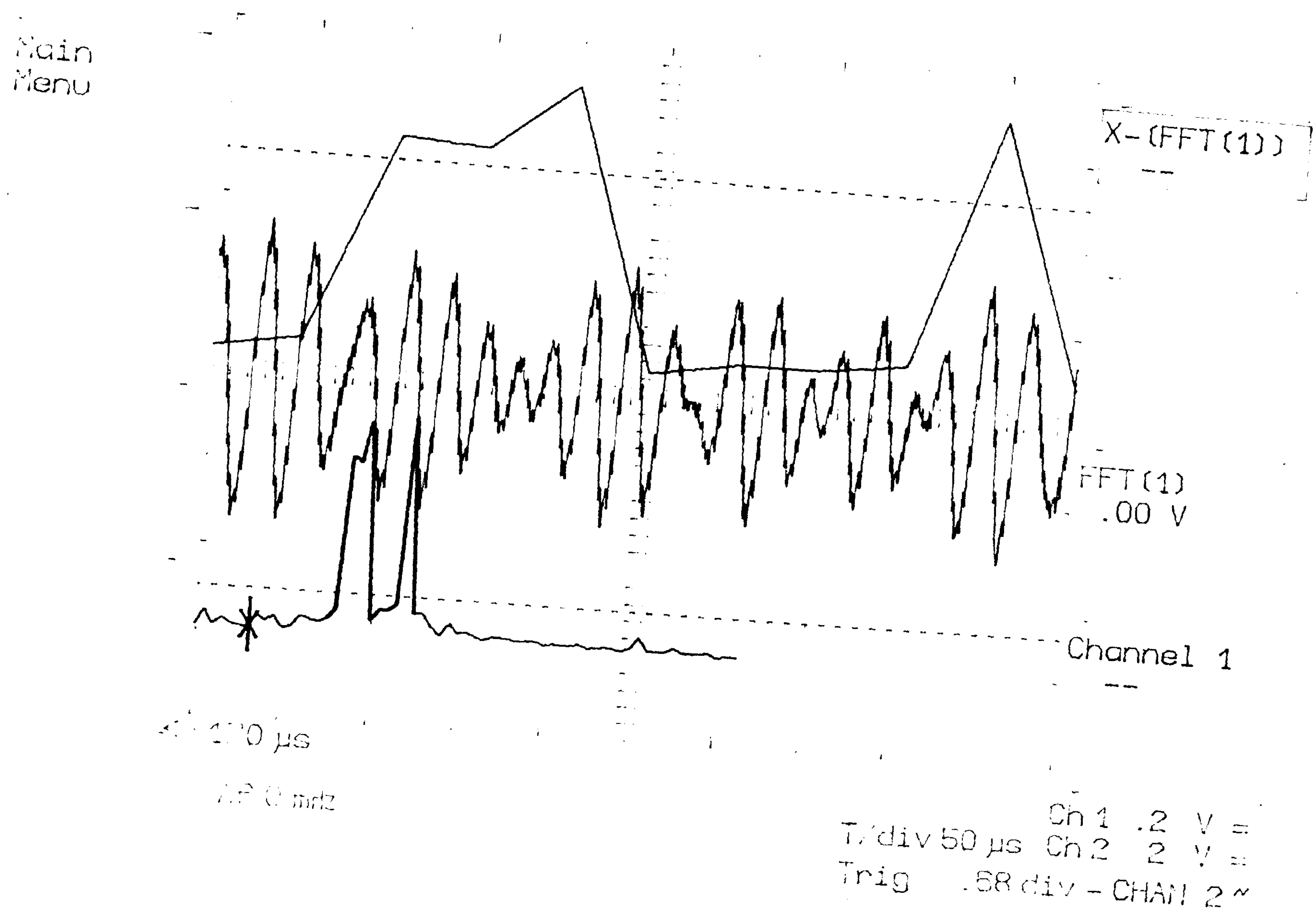

Main
Menu
FFT(1)
4 mV
Channel 1
--
Channel 2
--
← 160 µs
Δf 50.0 kHz
Ch 1>50 mV 50 Ω
T/div .1 ms Ch 2 2 V =
Trig .56 div - CHAN 2 ~

Figure B6



Main
Menu
X-(FFT(1))
FFT(1)
.00 V
Channel 1
Ch 1 .2 V =
T/div 50 µs Ch 2 2 V =
Trig .68 div - CHAN 2 ~

Figure B7

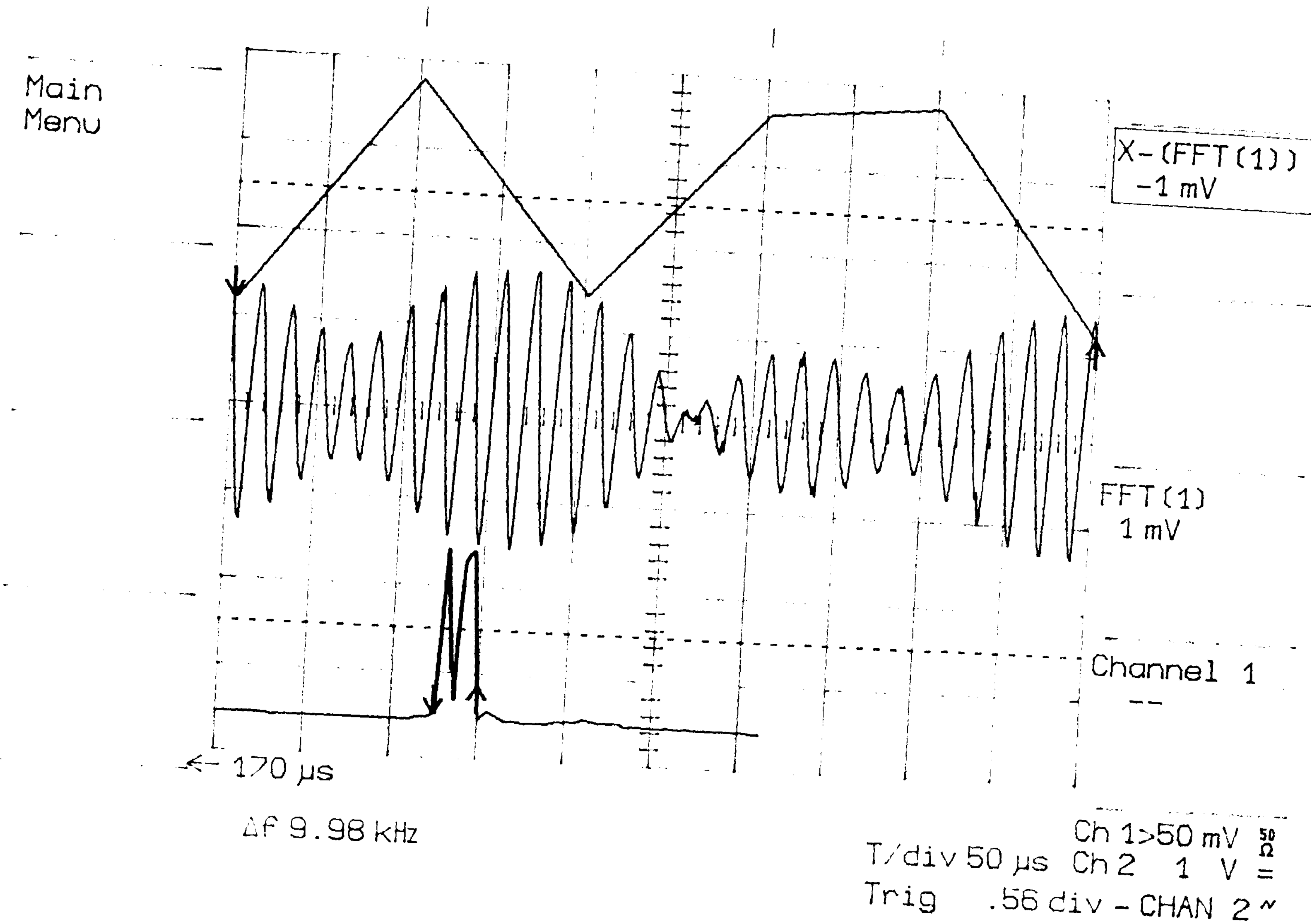

Main
Menu
X-(FFT(1))
-1 mV
FFT(1)
1 mV
Channel 1
--
← 170 µs
Δf 9.98 kHz
Ch 1>50 mV 50 Ω
T/div 50 µs Ch 2 1 V =
Trig .56 div - CHAN 2 ~

Figure B8

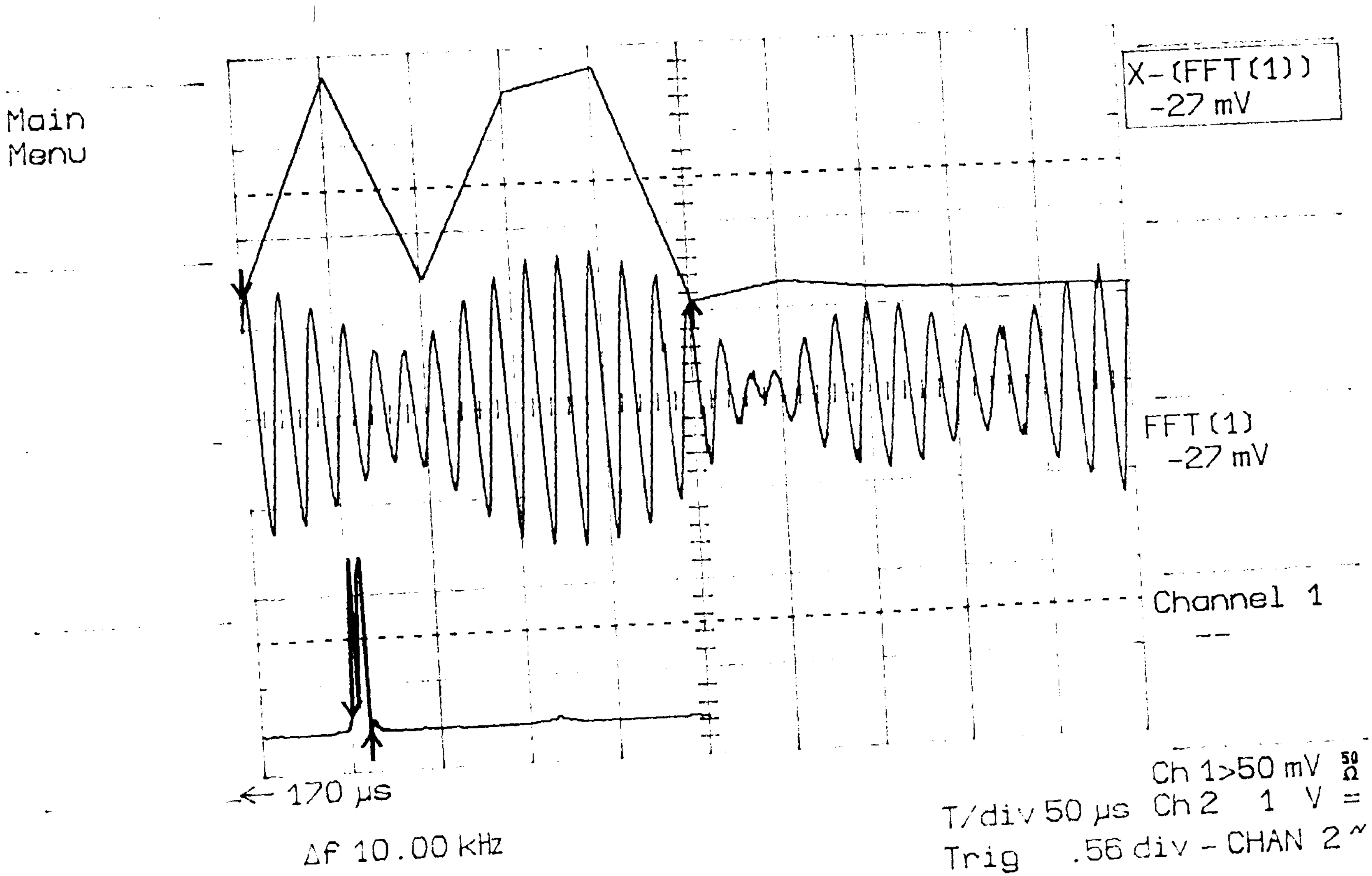

Main
Menu
X-(FFT(1))
-27 mV
FFT(1)
-27 mV
Channel 1
← 170 µs
Δf 10.00 kHz
Ch 1>50 mV 50 Ω
T/div 50 µs Ch 2 1 V =
Trig .56 div - CHAN 2 ~

Figure B9

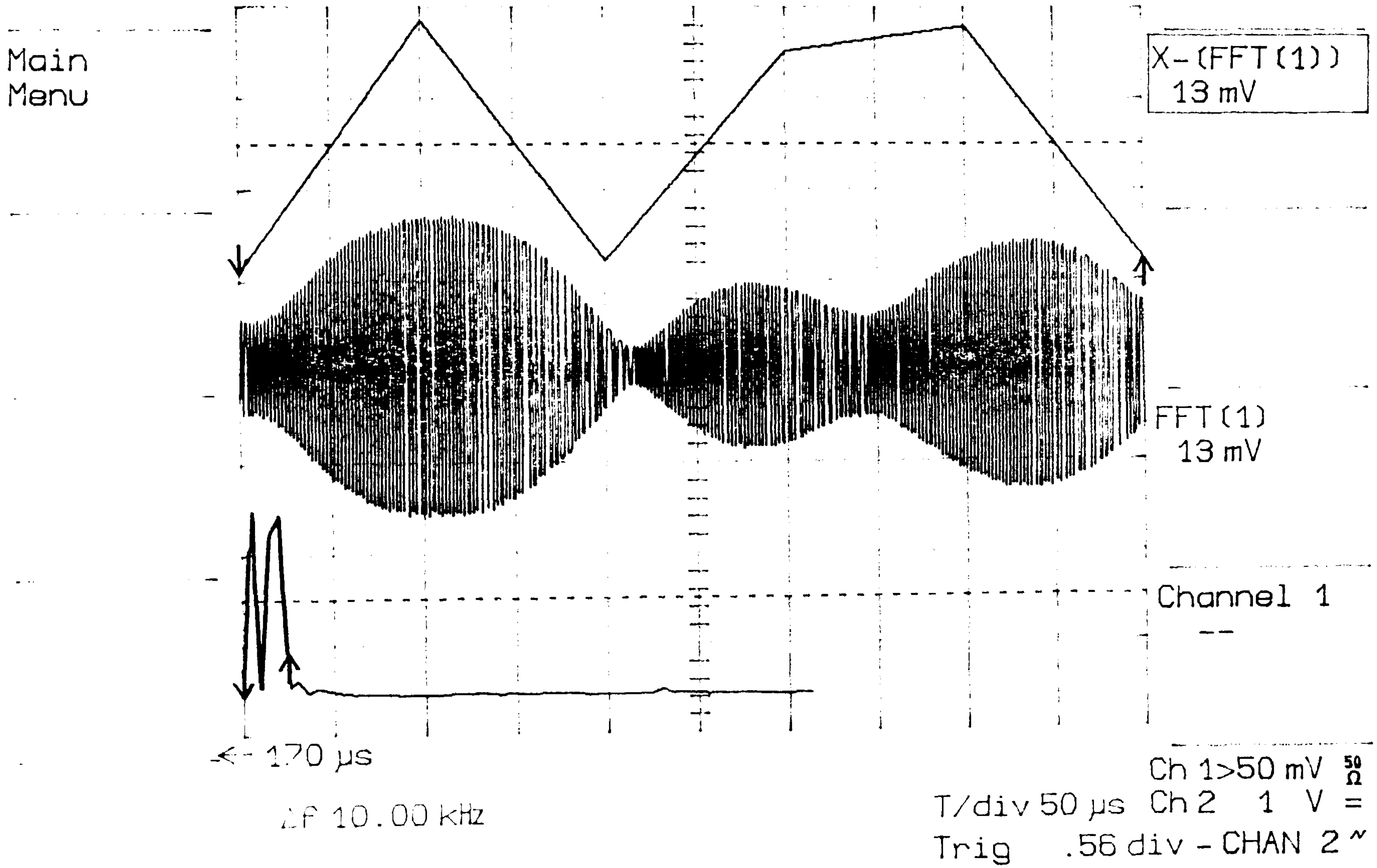

Main
Menu
X-(FFT(1))
13 mV
FFT(1)
13 mV
Channel 1
--
← 170 µs
ΔF 10.00 kHz
Ch 1>50 mV 50 Ω
T/div 50 µs Ch 2 1 V =
Trig .56 div - CHAN 2 ~

Figure B10

Fig 11

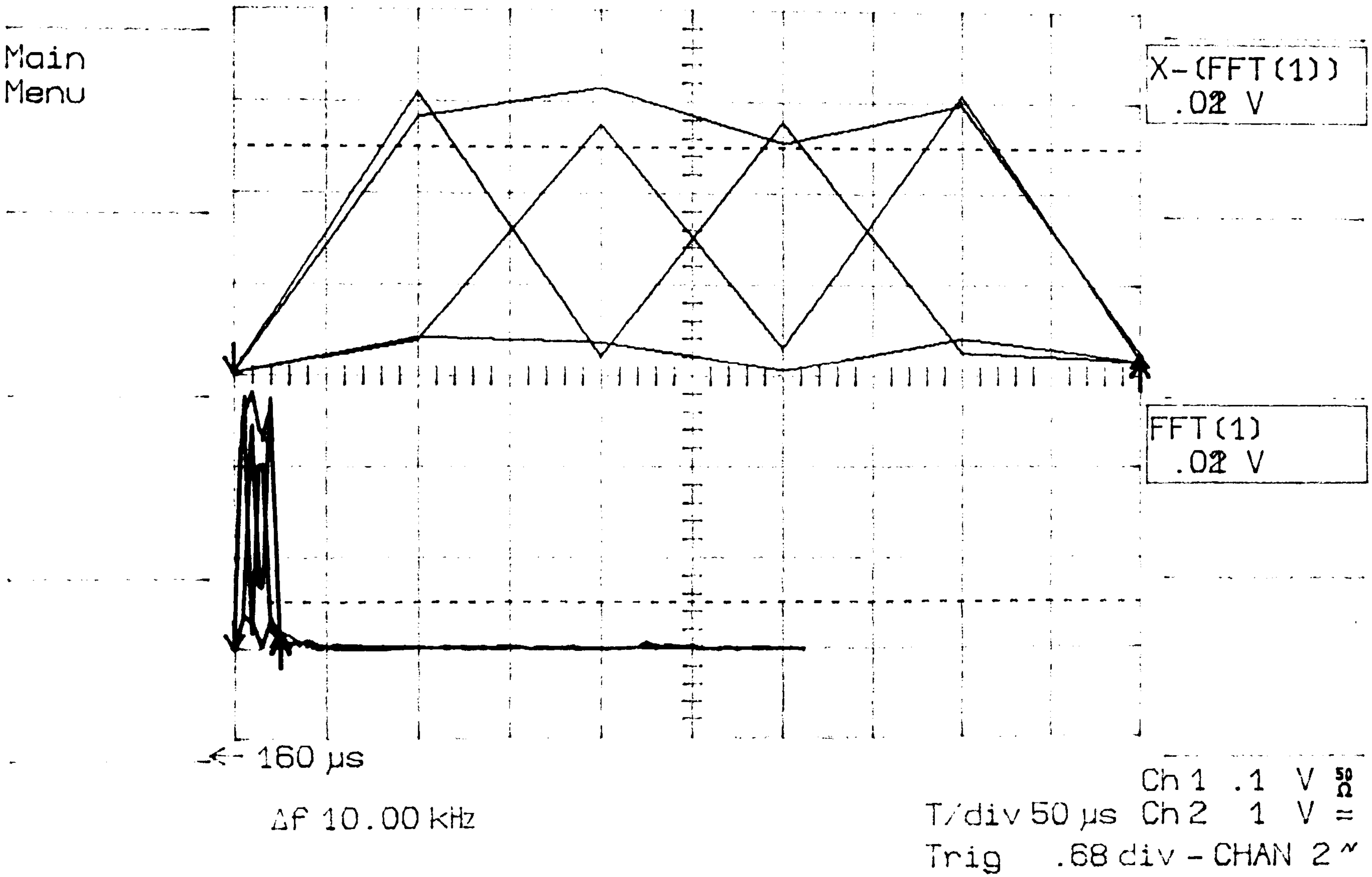


Figure B11

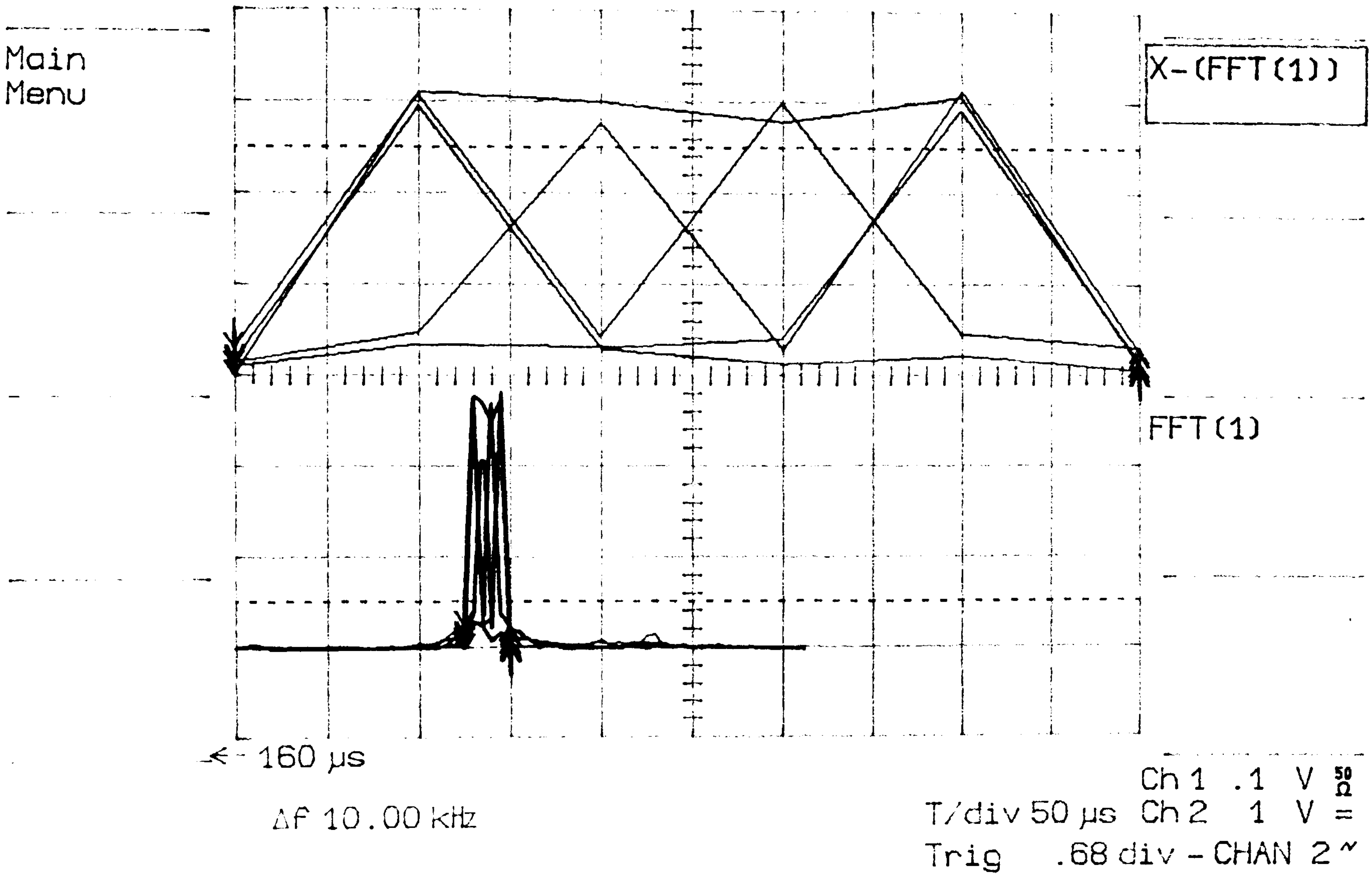

Main
Menu
X-(FFT(1))
FFT(1)
← 160 µs
Δf 10.00 kHz
Ch 1 .1 V 50Ω
T/div 50 µs Ch 2 1 V =
Trig .68 div - CHAN 2

Figure B12

Fig. 13.

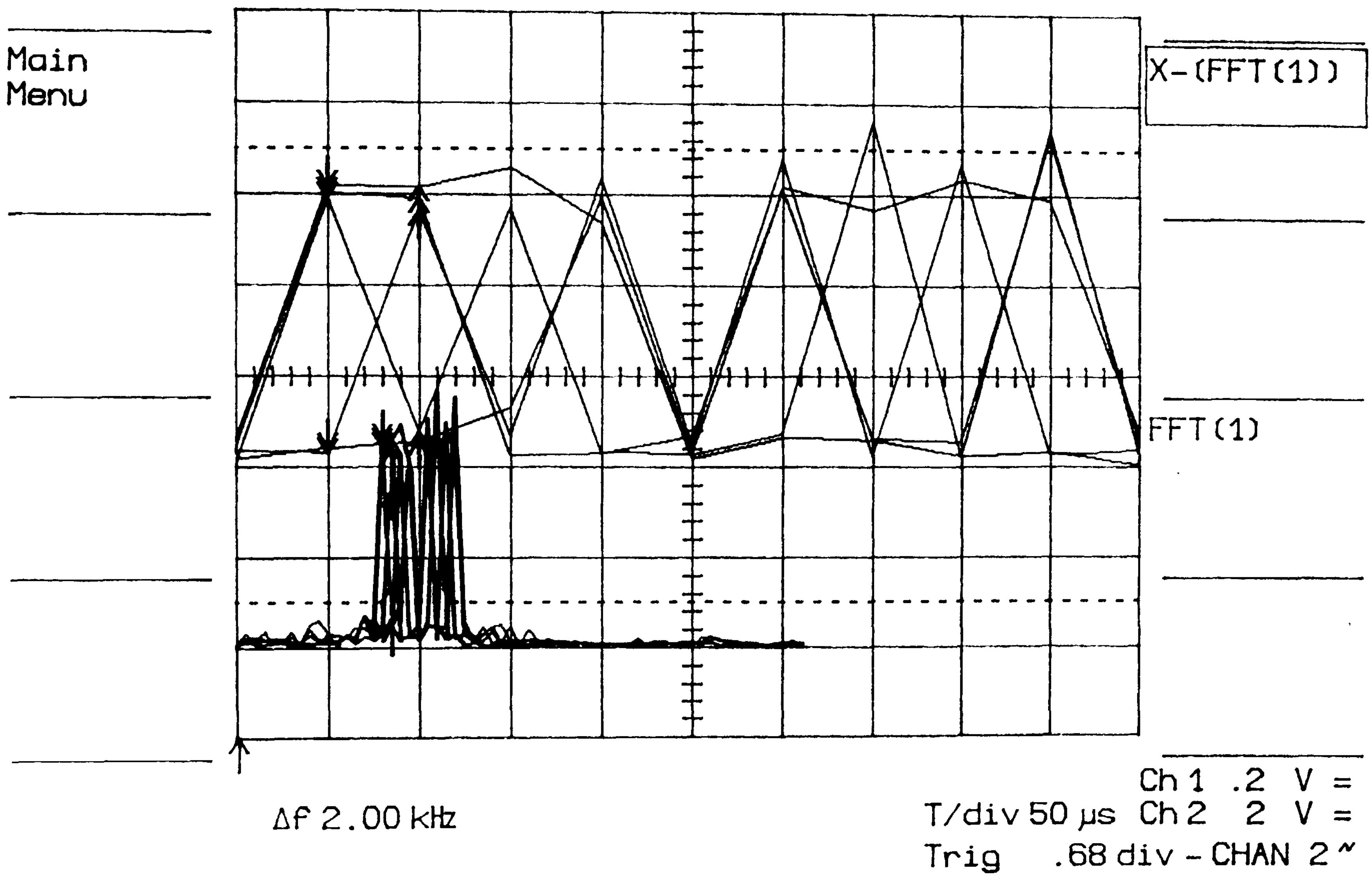


Figure B13

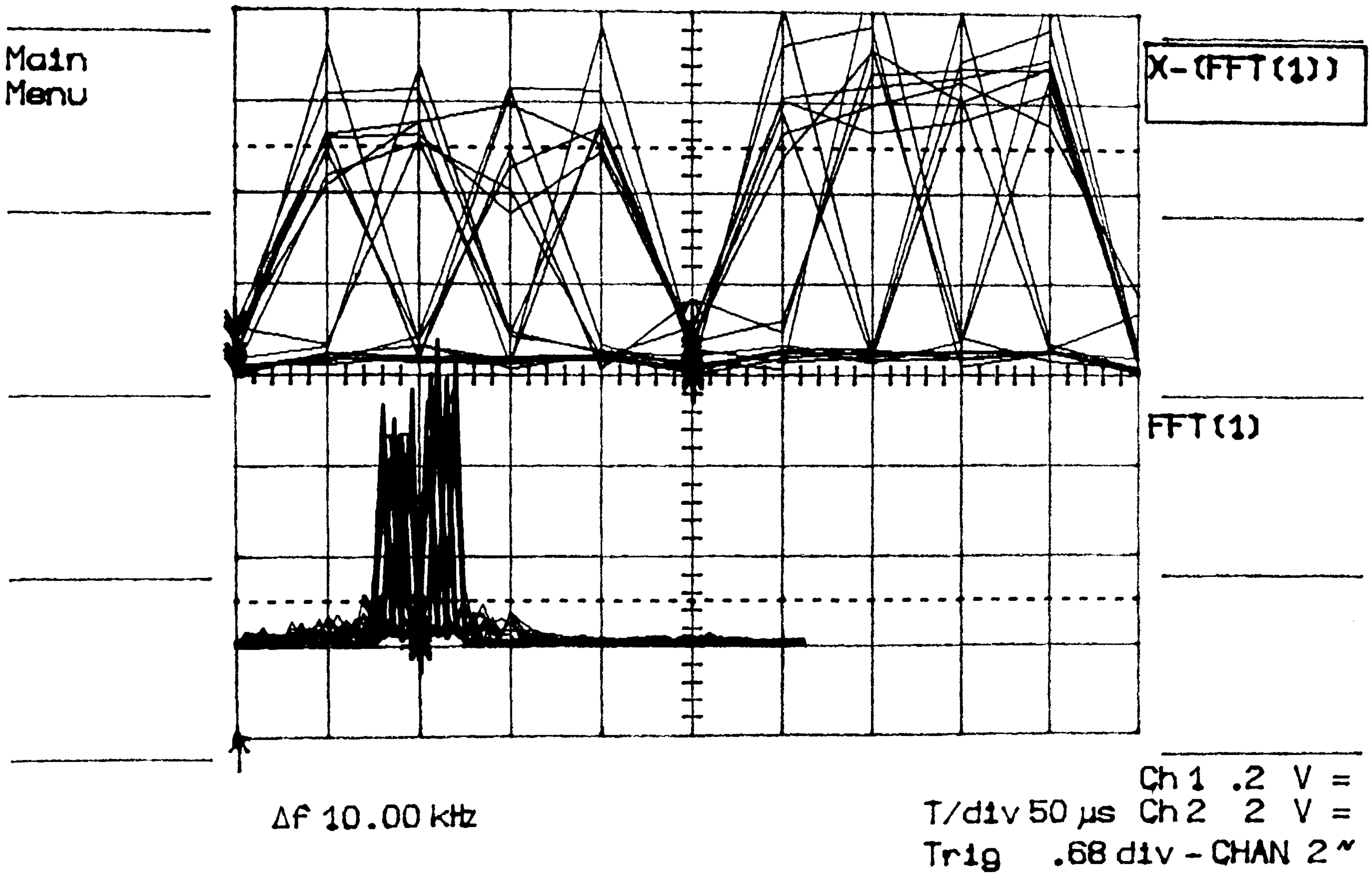

Main
Menu
X-(FFT(1))
FFT(1)
Δf 10.00 kHz
Ch 1 .2 V =
T/div 50 µs Ch 2 2 V =
Trig .68 div - CHAN 2

Figure B14

TAB C

APPENDIX C
FFT RECEIVER FIELD TESTS

The FFT based receiver was tested in field trials in and around Oxford, MS. The mobile laboratory used in the test setup is described by the block diagram in Figure C1. The monitor receiver was a Glenayre RF900 dual conversion receiver. The second local oscillator signal was a HP 8656A signal generator. By tuning the frequency of this signal, Mtel could bring the output signal (the second IF) to a desired frequency band. The output signal is further processed by FFT firmware built into the LeCroy 9400A digital oscilloscope.

Rather than build a clock recovery circuit for these tests (which is the means a fielded portable would use) the Mobile Laboratory received the link channel used to synchronize the transmitters in simulcast operation. Mtel used an IFR receiver as a mobile link receiver, with demodulation done in the TXC circuit, followed by clock generation. In order to match the FFT window to the baud interval delayed through the transmitters and data receivers, Mtel introduced additional delay in the clock path using the trigger delay of the LeCroy digital oscilloscope.

In the FFT setup Mtel chose a window size of 200 μs (20 μs/division on FFT analyzer plots) that corresponds to a single baud interval at a 5 kbaud rate.[12] All plots use logarithmic scaling, as defined by the "power spectrum" option in the FFT software. Thus,

[12] A 5 kbaud rate was chosen to deliberately stress the relatively short (7 miles) separation used in these tests.

the displayed spectrum values are in dBm units. This choice was made because of wide dynamic range of the signals received.

The number of FFT points for this calculation was chosen to be N=1000 so the full scale (Nyquist frequency) is 2.5 MHz. Mtel chose the LO frequency to place the multitone signal (930.9 MHz) in the middle of the displayed spectrum. The radio link channel (930.1 MHz) appears in the left hand part of the spectrum and the Mtel SkyTel channel (931.9375 MHz) in the right hand part of the scale. This arrangement allows comparison of the strength of these three signals.

The full frequency range of the spectrum is displayed in the lower left part of the pictures, while the expanded portion of the spectrum is plotted on the upper part of the picture. The expanded spectrum has a 5 kHz/division scale so that the tone separation fits the single division of the grid of the screen.

Figure C2 was taken near Big Star Grocery, roughly 1.5 miles from the first transmitter, and it shows three prominent peaks in full spectrum, each going out of bounds on the screen. The peaks are denoted as "R.L." (radio link channel), "4 Tones" (signal under investigation) and "MTEL" (the active paging channel). The expanded portion of the spectrum clearly shows the bit content of the signal (which is 1101, as noted above the grid). Note that the markers show the frequency separation between tones, displayed below the picture as ▲f 15.0 KHz, as well as amplitude deviation noted on the right hand side from the picture as -1.4 dB.

Figure C3 shows the signal spectrum taken near the second transmitter. Clearly the 4 tone signal is much stronger than the remote "R.L." and "MTEL" signals. Again, it is obvious that the bit content of the tones in this case is 1111.

Figure C4 shows the signal obtained during the search for the equi-signal overlap area. The first transmitter was fixed in the 1101 pattern, while the second transmitter was fixed in the 1011 pattern. In the overlap area Mtel found that the two middle tones registered nearly equal power while the outer tones registered higher power due to the simulcast effect.

The next three pictures (Figs. C5, C6 and C7) show FDEDs obtained at three sites in the Oxford area. Figure C5 was taken at the parking lot of the Holiday Inn Hotel, nearly 1 mile from the first transmitter. Figure C6 was obtained at the Mall of Oxford, less than a mile from the transmitter, but with a hill in between. Figure C7 was obtained at Clear Creek crossroad, nearly 7 miles from the first transmitter and 10 miles from the second transmitter. According to the numerical calculations of the transmitter coverage pattern, we expected simulcast overlap area at this point, but it was not independently confirmed by measurement. The corresponding plot of the signal spectrum obtained by a spectrum analyzer is given in Figure C8.

The general conclusion from these pictures is that the eye is open, *i.e.*, it can be decided whether a tone is on or off without error. A certain amount of noise is evident in all pictures. Further analysis and testing is needed to investigate different noise sources and the means of controlling them.

Mtel concluded that bit-error-rate testing was not appropriate at this phase of experimentation. Mtel has not yet adequately suppressed all interference and noise sources, and the construction of threshold circuits is a future task. As a rough experiment, Mtel evaluated performance by simply observing the FFT screen in consecutive frozen frames of FFT results with a known broadcast bit pattern (1101 in particular). Mtel visually estimated the threshold value (half way between minimum and maximum tones) and estimated the expected number of doubtful decision instances. At the pipe line office parking lot, roughly one mile from the first transmitter, Mtel found no doubt in 100 symbols. At the Big Star parking lot, roughly 1.5 miles from the transmitter, Mtel counted 5 doubtful symbols out of 100. While driving between these two sites, Mtel also counted 5 doubtful symbols out of 100. This data can be used as a rough estimate of the performance of the current experimental setup. Since many of these doubtful symbols would have, in fact, been correctly detected and since the "doubt" was in only one of the 4 bits in every symbol (yielding 5 doubtful bits out of 400 bits for the worst runs), even this crude experimental receiver appears to give performance that could easily be brought to acceptable levels by a simple error correcting code.

Conclusion

The field tests have confirmed the technical feasibility of an FFT based receiver. The frequency domain eye diagram is open, and detection of the bit pattern of tones within the baud interval without error is possible. Further study, however, is needed to reduce the various sources of interference and noise and improve receiver sensitivity.

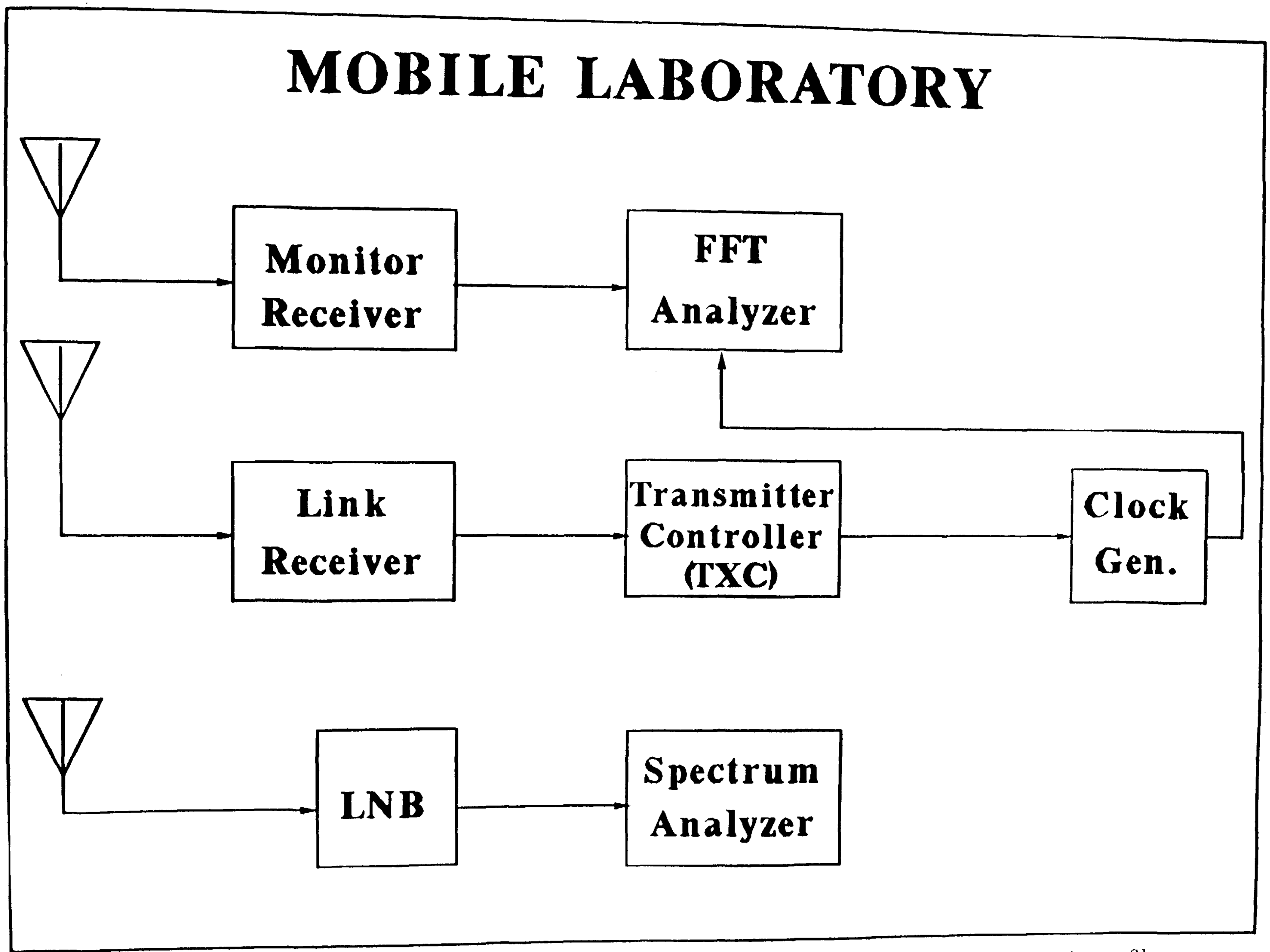
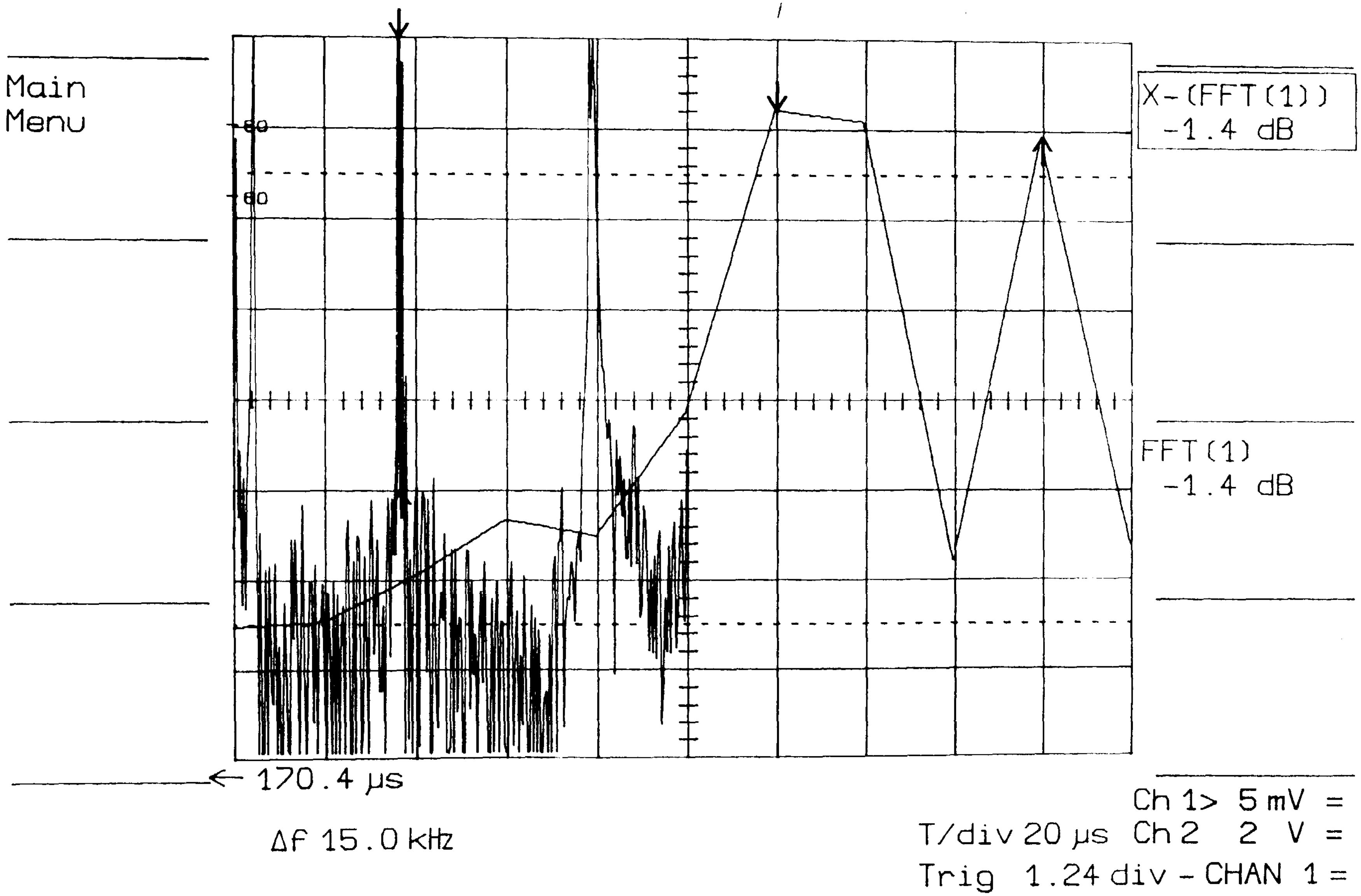

MOBILE LABORATORY
Monitor Receiver
FFT Analyzer
Link Receiver
Transmitter Controller (TXC)
Clock Gen.
LNB
Spectrum Analyzer

Figure C1



Main
Menu
X-(FFT(1))
-1.4 dB
FFT(1)
-1.4 dB
← 170.4 µs
Δf 15.0 kHz
Ch 1> 5 mV =
T/div 20 µs Ch 2 2 V =
Trig 1.24 div - CHAN 1 =

Figure C2

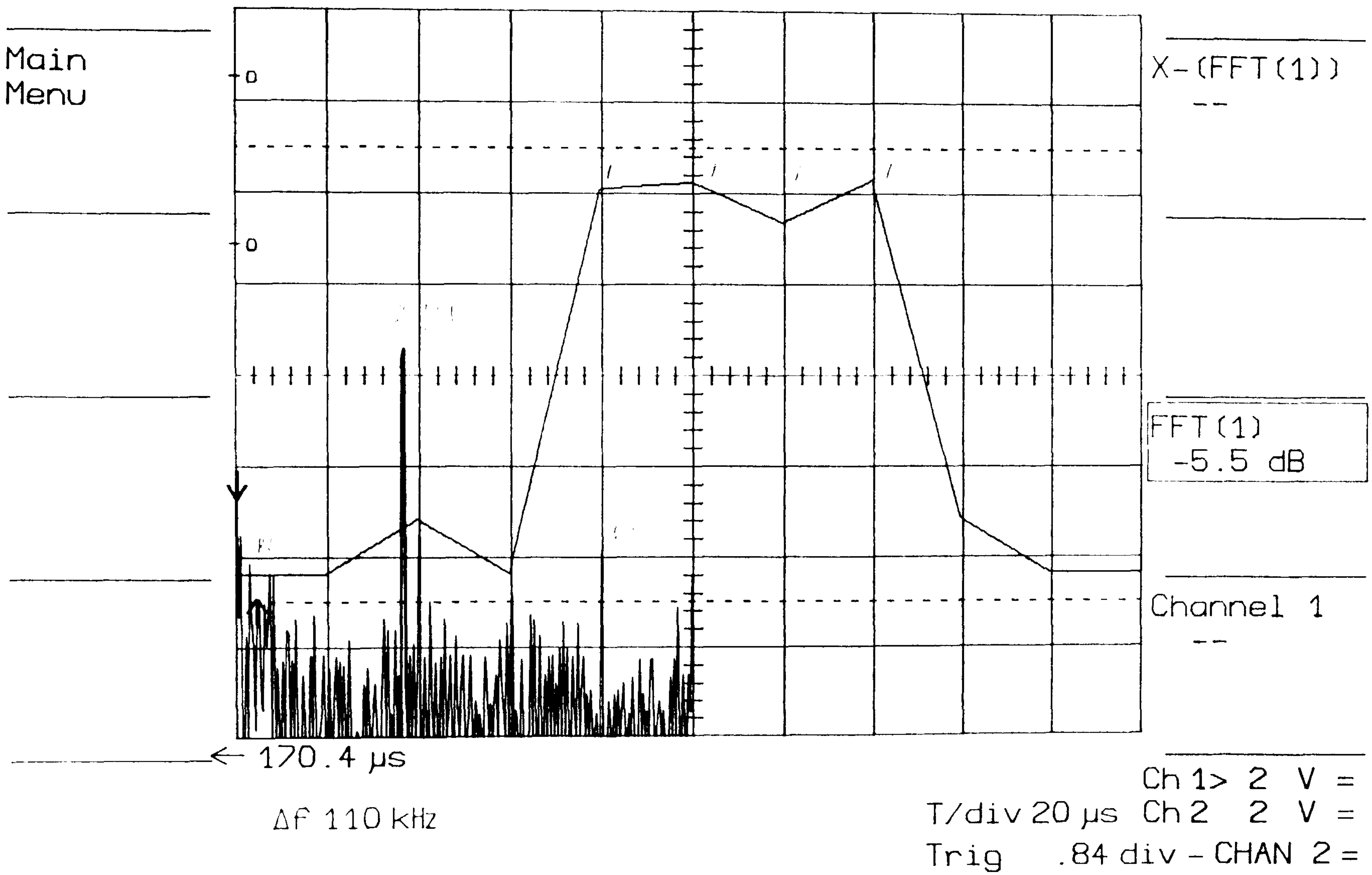

Main
Menu
X-(FFT(1))
--
FFT(1)
-5.5 dB
Channel 1
--
← 170.4 µs
Δf 110 kHz
Ch 1> 2 V =
T/div 20 µs Ch 2 2 V =
Trig .84 div - CHAN 2 =

Figure C3

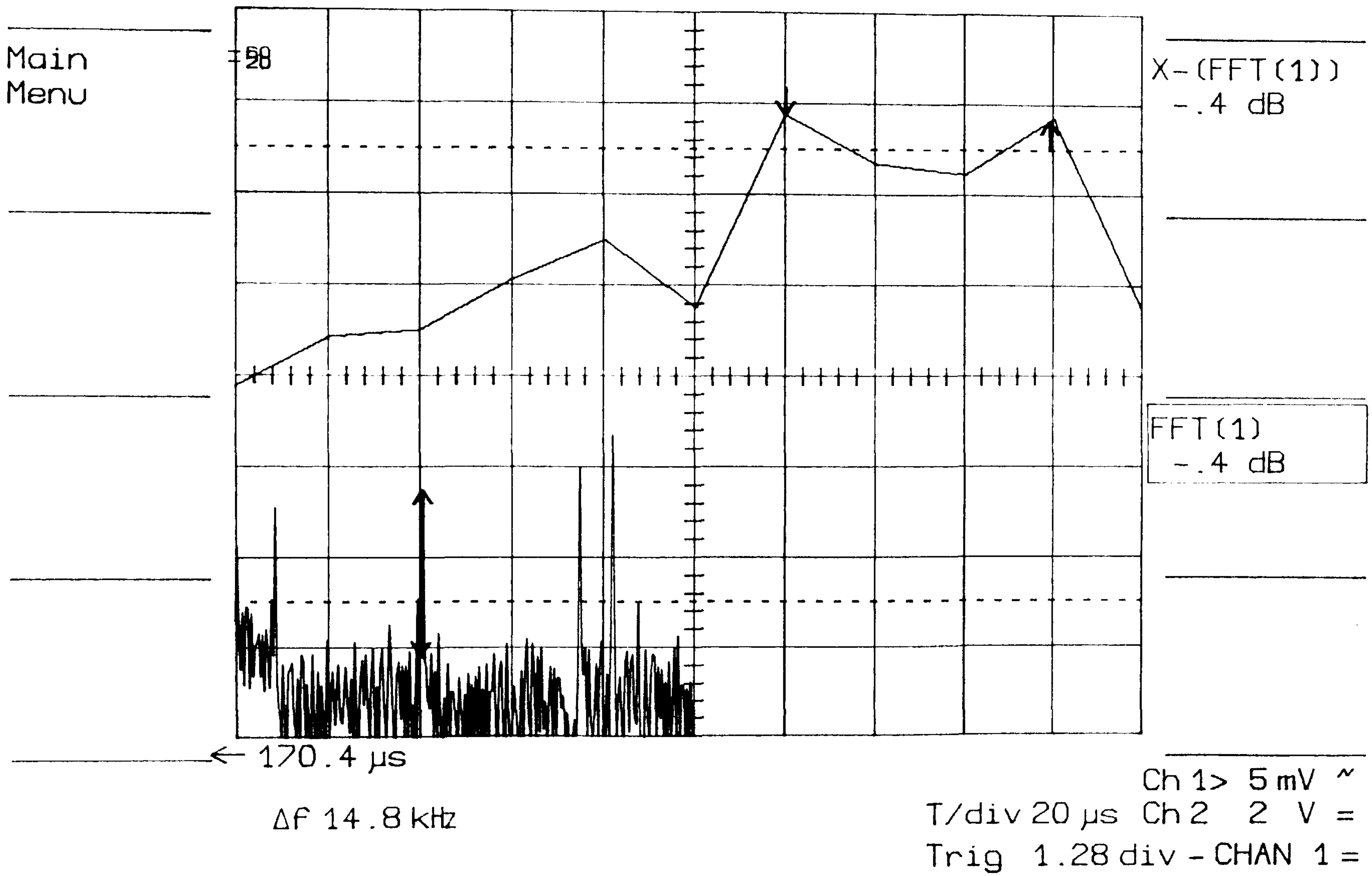

Main
Menu
X-(FFT(1))
-.4 dB
FFT(1)
-.4 dB
← 170.4 µs
Δf 14.8 kHz
Ch 1> 5 mV ~
T/div 20 µs Ch 2 2 V =
Trig 1.28 div - CHAN 1 =

Figure C4